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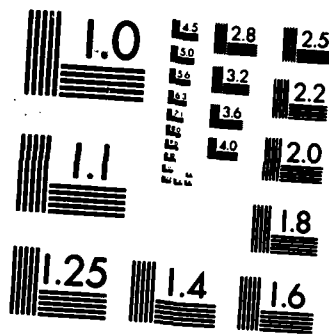D A SANTAVICCA 10 JAN 86 AFOSR-TR-86-1004 AFOSR-84-0224

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MICROCOPY RESOLUTION TEST CHART
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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
Unclassified	None

2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	Approved for public release, distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
	AFOSR-TR- 86-1004

6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
The Pennsylvania State Univ.		Air Force Office of Scientific Research

6c. ADDRESS (City, State and ZIP Code)	7b. ADDRESS (City, State and ZIP Code)
Mechanical Engineering Building University Park, PA 16802	Bolling AFB, D.C. 20332-6448

8a. NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Office of Scientific Research	8b. OFFICE SYMBOL (If applicable) AFOSR/NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR84-0224

8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.			
Bolling AFB, D.C. 20332-6448	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
	61102F	2308	A2	

11. TITLE (Include Security Classification)
Transient Catalytic Combustion

12. PERSONAL AUTHOR(S)
D. A. Santavicca

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Annual	FROM 9/30/84 TO 9/30/85	10 January 1986	26

16. SUPPLEMENTARY NOTATION

OCT 16 1986

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Catalytic Combustion
21	01		Catalytic Ignition
21	02		Premixed Turbulent Combustion

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The results of an experimental study of the catalytic ignition of lean propane-air mixtures on platinum in a stacked-plate catalytic combustor are presented. The effects of inlet temperature, equivalence ratio and gas velocity on the ignition transient were investigated. The ignition process was characterized in terms of the substrate axial temperature profile and the exhaust gas CO and CO_2 concentrations measured as a function of time after the fuel was turned on. Ignition was always found to occur first near the leading edge of the catalyst as indicated by the more rapid heat-up of the front end of the catalyst. The downstream end of the catalyst was found to heat up more slowly and to be strongly dependent on convective heat transfer from the front of the catalyst. Increased inlet temperature, equivalence ratio and velocity were all found to shorten the ignition transient and to lead to increased steady state peak substrate temperatures. Increased velocity also caused

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
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the peak substrate temperature to move further toward the back of the catalyst. For the specific conditions studied, the initial ignition rate was found to be surface reaction rate controlled at higher velocities (above 2 m/s) but at lower velocities (below 2 m/s) the initial ignition rate was found to depend both on the surface reaction rate and the mass transport rate. The transient ignition measurements also clearly revealed the fact that complete conversion can be achieved at substrate temperatures which are several hundred degrees below steady state.

Initial experiments on oscillating catalytic combustion were also conducted and results for two oscillating and an equivalent nonoscillating cases are presented. The results demonstrate the ability to selectively exclude the CO gas phase reactions by the appropriate selection of the fuel on-off modulation frequency.

A status report on a new project studying the effect of turbulence intensity and scale on premixed turbulent flame structure is also presented. In this study LDV is used to characterize the turbulence, where a recently developed two-point LDV system is used to directly measure the turbulence length scale, and 2-D flow visualization is used to characterize the turbulent flame structure. The results from this research will be used to evaluate and improve existing phenomenological models of premixed turbulent flame structure and flame propagation.

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RESEARCH OBJECTIVES

Transient Catalytic Combustion

Motivated by the potential advantages of catalytically assisted over conventional combustion, there have been a number of studies of the feasibility of applying catalytic combustion to practical combustion systems over the past ten years. The demonstrated advantages include lower emissions, higher efficiency, increased operational stability, stable operation at lower equivalence ratios, improved pattern factor and wider fuel specifications. Despite these advantages, catalytically assisted combustion is not widely used primarily because of problems associated with catalyst durability, both in terms of thermal shock failure and loss of activity when operated for prolonged periods at high temperatures. Although these are basically material science related problems, the temperature and temperature gradients which the catalyst and catalyst substrate are exposed to are determined by the complex interaction and coupling of numerous physical and chemical subprocesses including axial and radial convection of species, heat and momentum; axial heat transfer in the substrate by conduction and radiation; and gas phase and surface chemical reactions. Therefore any solution to the problem of catalyst durability will require an understanding of these physical and chemical subprocesses which actually determine the catalyst's temperature and temperature gradient profile.

The objective of this experimental study was to better understand the relative importance and effect of these subprocesses, during both catalytic ignition, when the largest temperature gradients are expected, and steady state operation, when the maximum temperatures are expected. These experiments were intended to complement a number of recent attempts to

numerically model transient catalytic combustion and represent the first transient catalytic combustion experiments to be reported. The experiments conducted in this study consisted of measurements of the catalyst substrate temperature profile and exhaust gas composition during the ignition process following the sudden turn-on of the fuel. In addition, laser fluorescence measurements of hydroxyl radicals produced by catalytic surface reactions were planned in order to assess possible effects on the gas phase chemistry, but were not able to be made during the one year duration of this part of the project.

A second objective which evolved during the course of this work was a preliminary study of the possible advantages of operating in an unsteady or oscillating mode. Unsteady operation of chemical reactors has been studied for many years where demonstrated advantages over equivalent steady state operation include greater conversion efficiency and increased product selectivity [1-5]. Unsteady operation refers to periodically varying one or more of the reactor operating parameters, such as the fuel flow rate, the air flow rate or the gas temperature. The improved performance observed with unsteady operation is generally attributed to the nonlinear chemical reaction rates, the different time scales of the subprocesses in relation to the period of the unsteady modulation and/or the enhanced mass and thermal transport due to disturbance of the boundary layer profile [5,6]. The ignition experiments very clearly demonstrated the time scales for the different subprocesses and in turn suggested possible modes of oscillating operation which were investigated and compared to equivalent steady state operation.

Premixed Turbulent Combustion

There are numerous subprocesses which determine the performance, efficiency and emissions characteristics of gas turbine combustors, including fuel spray atomization, fuel spray vaporization, turbulent mixing and turbulent combustion, both premixed and non-premixed. The motivation for this research is the need for fundamental knowledge regarding the effect of turbulence on premixed turbulent combustion, particularly its effect on flame structure since it is through changes in the flame structure that the flame speed and combustion rate are increased. In studying the effect of turbulence on premixed turbulent flames it is important to characterize the turbulence in a way which distinguishes between large scale turbulent fluctuations which distort and wrinkle what is basically a laminar flame and small scale turbulent fluctuations which increase the heat and mass transport within the flame. Both phenomena lead to increased overall flame speed and combustion rate but by fundamentally different mechanisms. It is also important to directly measure not only the turbulence intensity but also the turbulence length scale because of its extensive use in the formulation of mathematical models of premixed turbulent combustion, in hypothesis regarding the structure of premixed turbulent flames, in models of turbulent transport coefficients and in laminar to turbulent flame speed correlations.

Experiments have been initiated in an atmospheric pressure flow reactor and will in the coming year be initiated in a high pressure turbulent flow reactor using premixed propane and air. The turbulent flame is stabilized in an optically accessible, diverging test section. The turbulence is generated at the inlet to the test section and is characterized using LDV where a recently developed two-point collection

optics system is employed to obtain the turbulent length scale. The flame structure is determined using 2-D flow visualization.

This research will specifically address questions regarding the relationship between turbulence intensity and scales and turbulent flame structure, the relative importance of small and large scale turbulent fluctuations on turbulent flame structure as well as the effect of combustion on turbulence intensity and scales over a broad range of turbulence Reynolds numbers and Damköhler numbers. The results will be used to evaluate and improve current phenomenological models of premixed turbulent combustion.

STATUS OF RESEARCH

During the first year of AFOSR Grant 84-0224, progress was made in three areas as summarized in the following sections.

Turbulent Combustion Laboratories

The Turbulent Combustion Laboratory, operated under the direction of Dr. D.A. Santavicca, was constructed and made operational during this past year. This is a 1500 square foot laboratory with five interconnected test cells housing two atmospheric pressure flow reactors and one high pressure (20 atm) flow reactor, with a second to be completed by September 1986. The flow reactors are capable of operating with inlet temperatures up to $1000^\circ K$, gas velocities up to 20 m/sec and a broad range of turbulence intensities and scales. The high pressure flow reactor was designed to be capable of simulating the flow field conditions in both gas turbine combustors and IC engines. The flow reactors are modular in design allowing for a variety of test section configurations, including those with optical access for the use of advanced laser diagnostic techniques. The catalytic ignition experiments were conducted in one of the atmospheric pressure flow reactors. The premixed turbulent flame structure experiments are currently being conducted in the second atmospheric pressure flow reactor and will next year be done at high pressure in the second high pressure turbulent flow reactor.

The instrumentation which is available in the Turbulent Combustion Laboratory includes a Nd:YAG pulsed laser, a pulsed dye laser, an ultraviolet double monochrometer, an argon ion based LDV system, a two-point LDV collection optics system, a 128 x 128 diode array camera and

video-processing system, a gas chromatograph, CO and CO_2 NDIR gas analyzers and an IBM PC/XT based data acquisition/processing/graphics system.

Transient Catalytic Combustion

The transient catalytic combustion experiments were conducted in a stacked plate catalytic combustor consisting of nine flat catalytic plates (100 mm long, 50 mm wide, 1 mm thick) spaced 6 mm apart. The catalyst plates (suppled by W. Retallick) were made from a steel alloy substrate, with an aluminum oxide barrier and an outer coating of platinum. Holes were drilled in the side of the center plate at six axial locations and chromel alumel thermocouples were inserted into these holes for measurement of the plate's axial temperature profile. All experiments were with lean propane-air mixtures at atmospheric pressure. In addition to measurements of the catalyst substrate axial temperature profile, the exhaust gas CO and CO_2 concentrations were measured using a water-cooled gas sampling probe and on-line non-dispersive infrared gas analysis. The sampling probe was located 25 mm downstream the catalyst exit. The six thermocouple and two gas analyzer outputs where recorded every 15 seconds during the transient experiments using a data logger. The response time of the combined gas sampling and analysis system was determined by the following experiment. Carbon dioxide was supplied to the fuel delivery system at 30 psig and the flow reactor was set to a typical operating velocity and temperature. The fuel solenoid valve was then opened and after seventy-five seconds closed. The resultant carbon dioxide analyzer output is shown in Figure 1. The turn-on transient, which is representative of the response time of the fuel delivery system, is approximately 15 seconds (to reach 90% of steady state).

The turn-off transient, which is representative of the response time of the gas sampling and analysis system is less than 3 seconds.

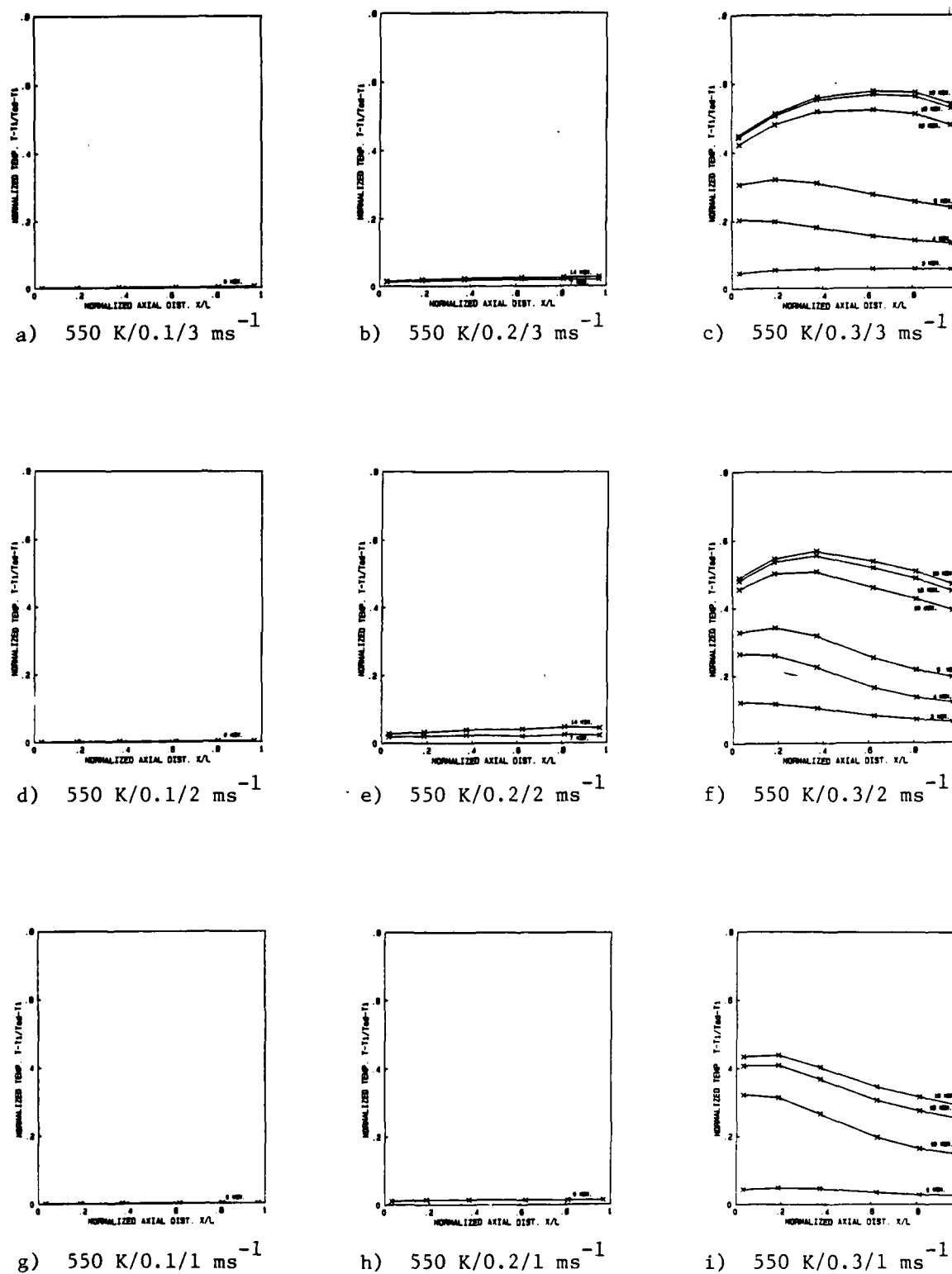Figure 1: Gas Sample/Analysis
System Response
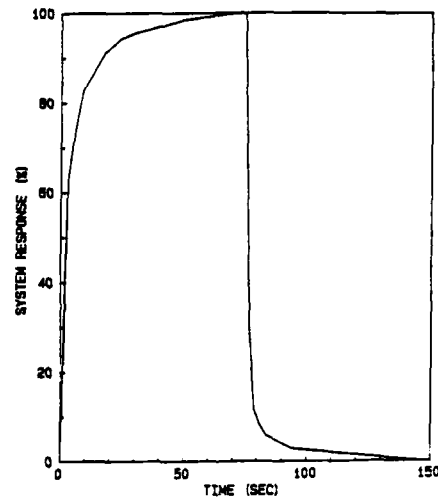
Ignition Experiments: In the ignition experiments the inlet temperature and velocity were fixed, the fuel solenoid valve was opened and the transient response of the stacked plate catalytic combustor was monitored by measurements of the substrate's axial temperature profile and exhaust gas CO and CO_2 concentrations. The ignition experiments were conducted at inlet temperatures of 550 and 600 K; at reference velocities of 1, 2, and 3 meters/second; and at steady state equivalence ratios of 0.1, 0.2 and 0.3. (At 600 K and an equivalence ratio of 0.3, tests were also conducted at 4 and 5 meters/second.)

For an inlet temperature of 550 K, the effects of equivalence ratio and gas velocity on the transient and steady state substrate axial temperature profile and the CO and CO_2 emissions are shown in Figures 2 and 3 respectively. The normalized substrate axial temperature profiles are

shown at various times as indicated and the CO and CO_2 concentrations at the exit of the catalyst bed are shown plotted versus time. The normalized substrate temperature is defined as the substrate temperature minus the initial substrate temperature divided by the adiabatic flame temperature minus the initial substrate temperature, where the adiabatic flame temperature is based on the inlet temperature and equivalence ratio. In these nine runs, ignition (as indicated by a pronounced increase in the substrate temperature shown in Figure 2) was found to occur only at an equivalence ratio of 0.3. Ignition is observed to take place first near the leading edge of the catalyst plates causing the front end of the catalyst to heat up, while the backend of the catalyst appears to heat up more slowly. The effect of increasing the gas velocity is to cause the peak temperature with increasing time to move further toward the back of the catalyst and to result in greater steady state peak temperatures. The former is due in part to greater convective heat transport from the front to the back of the catalyst but also to the fact that with increasing fuel flow rate the fuel persists further into the catalyst before being totally consumed. The increasing steady state peak temperature is due to the increased fuel flow rate, i.e., the increased overall heat release rate, even though increased convective heat transfer tends to counteract this effect. Note that the surface temperature never reaches the adiabatic flame temperature due to convective heat transfer to the gas and radial heat loss through the test section walls.

A particularly interesting observation is that for all three velocities the conversion efficiency reaches greater than 90% of its steady state value before the peak temperature reaches 900 K (a normalized temperature of 0.3) whereas the steady state peak temperatures are as high
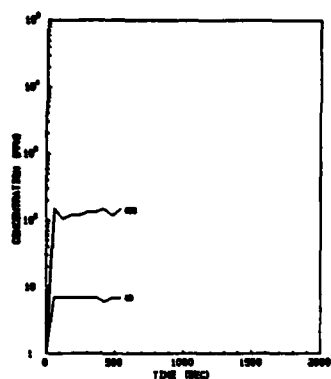
a) 550 K/0.1/3 ms^{-1} b) 550 K/0.2/3 ms^{-1} c) 550 K/0.3/3 ms^{-1}

d) 550 K/0.1/2 ms^{-1} e) 550 K/0.2/2 ms^{-1} f) 550 K/0.3/2 ms^{-1}

g) 550 K/0.1/1 ms^{-1} h) 550 K/0.2/1 ms^{-1} i) 550 K/0.3/1 ms^{-1}

Substrate Axial Temperature Profiles at the Indicated Times and
at the Indicated Inlet Temperature/Equivalence Ratio/Velocity

Figure 2

as 1150 K. This suggests that by increasing the heat loss from the
catalyst and consequently lowering the catalyst temperature, that the
catalyst's lifetime could be increased with minimal reduction in catalyst
performance. This observation should not be misinterpreted as evidence
that the fuel conversion rate is mass transfer limited, i.e., independent
of the surface reaction rate, but a result of the fact that under these
conditions once the catalyst temperature reaches 900 K the catalyst length
is longer than it need be for complete fuel conversion.

For a given inlet temperature the ability to achieve ignition can be
limited by the fact that the equivalence ratio can not be increased above a
certain value determined by the maximum steady state temperature the
catalyst can withstand. The above observation points to the fact that if
the heat loss from the catalyst can be increased then it would be possible
to operate with larger equivalence ratios which would in turn lower the
inlet temperature required for ignition. Note that if the increased heat
loss is due to increased convective heat transfer to the exhaust gas it is
not a loss from an overall systems point of view.

Although for an inlet temperature of 550 K there is no significant
temperature rise when the equivalence ratio is 0.2, there is evidence of
catalytic surface reactions indicated by the CO_2 measurements shown in
Figure 3. For an equivalence ratio of 0.3, however, there is a large
increase in CO_2 again indicating ignition at these conditions. The fact
that the CO_2 is due almost entirely to surface reactions is evidenced by
the absence of CO which only appears in very small concentrations very late
in the transient for the two higher velocity, equivalence ratio equal to
0.3 cases. The presence of CO indicates that the gas temperature has
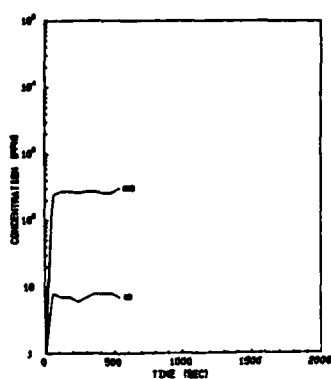increased to the point where gas phase reaction rates become significant.
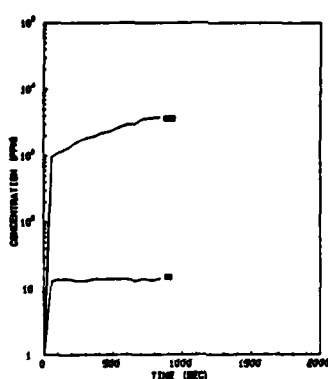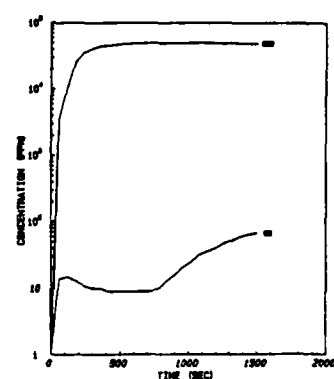
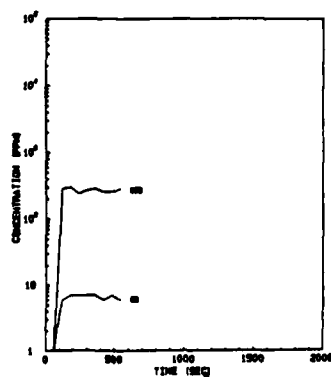a) 550 K/0.1/3 ms^{-1} b) 550 K/0.2/3 ms^{-1} c) 550 K/0.3/3 ms^{-1}
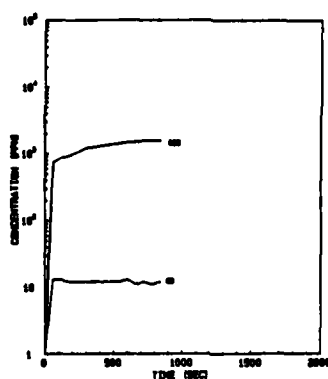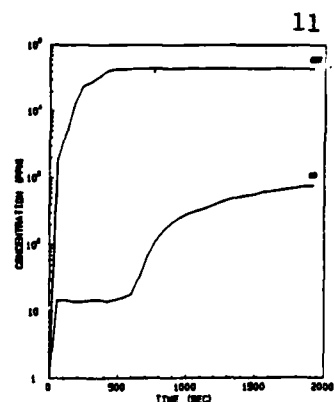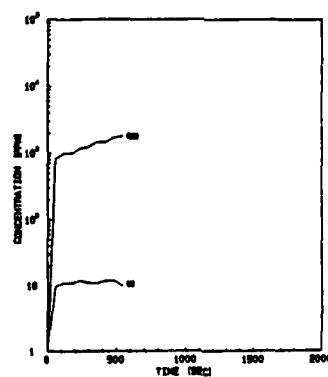
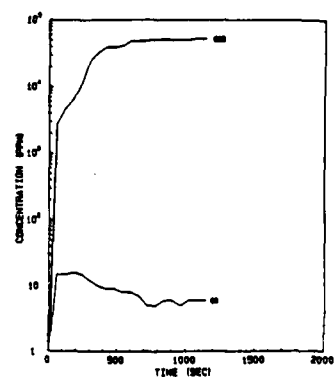d) 550 K/0.1/2 ms^{-1} e) 550 K/0.2/2 ms^{-1} f) 550 K/0.3/2 ms^{-1}
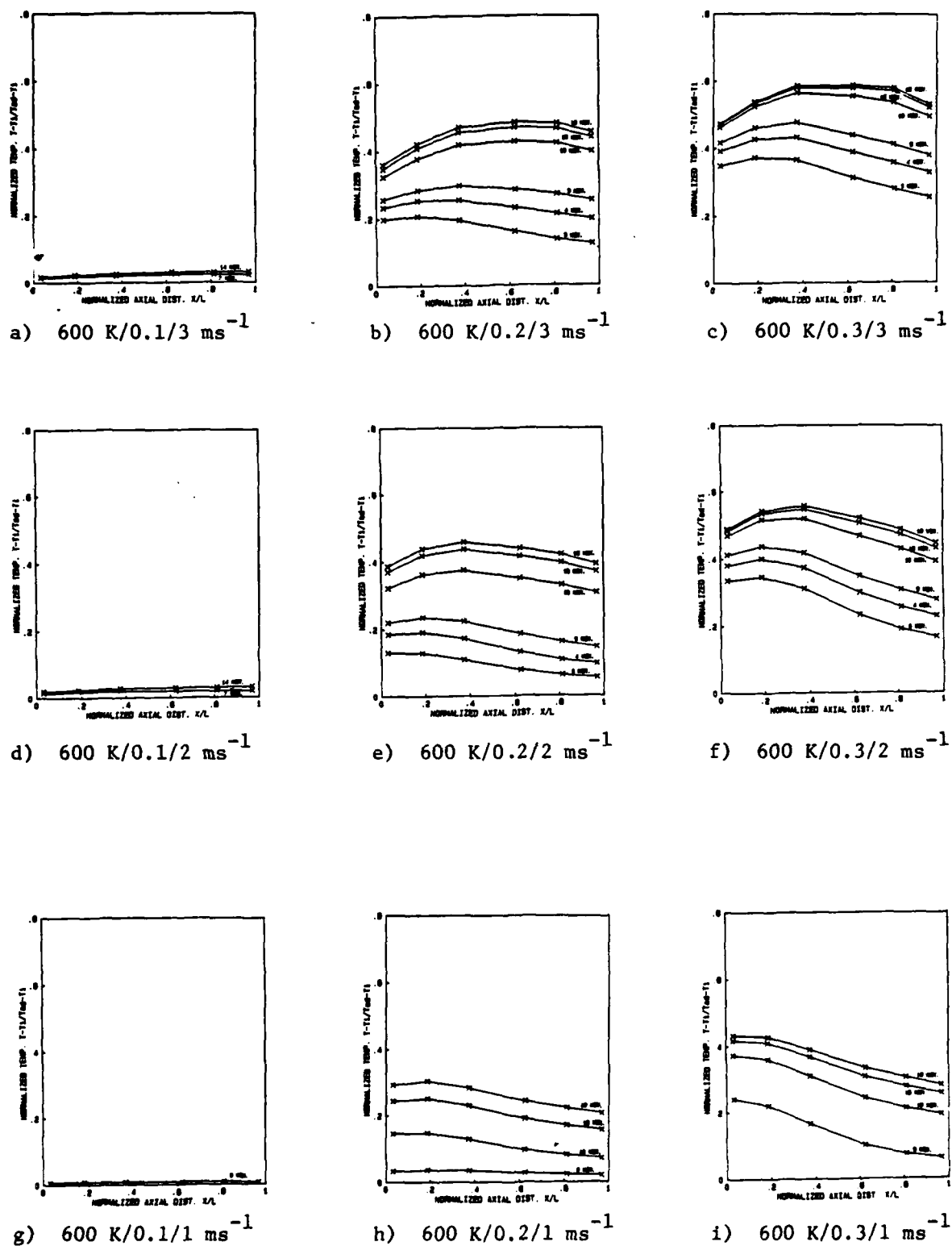
g) 550 K/0.1/1 ms^{-1} h) 550 K/0.2/1 ms^{-1} i) 550 K/0.3/1 ms^{-1}

Exhaust Gas CO and CO_2 Concentration Versus Time at the
Indicated Inlet Temperature/Equivalence Ratio/Velocity

Figure 3

The fact that the CO concentrations are so low indicates that the gas phase reactions occur toward the downstream end of the catalyst where the gas temperature is greatest and the remaining fuel concentration is smallest. Increased gas velocity is shown to result in earlier and greater CO emissions which is due to increased convective heat transfer from the catalyst to the gas phase.

For an inlet temperature of 600 K, the effects of equivalence ratio and gas velocity on the transient and steady state substrate axial temperature profiles and the CO and CO_2 emissions are shown in Figures 4 and 5. With the increased inlet temperature, ignition was found to occur at an equivalence ratio of 0.2. The general trends observed at 550 K are also observed at 600 K, the main difference being that for a given equivalence ratio and velocity the time required to reach steady state is shorter at 600 K. The steady state peak temperatures are also greater by an amount very nearly equal to the difference in the inlet temperature, and still considerably below the adiabatic flame temperature. Again, however, it is shown that the catalyst could actually operate at considerably lower steady state substrate temperatures with the same overall conversion efficiency.

Insight into whether the catalytic ignition process is mass transfer or surface reaction rate controlled can be obtained from Figure 6. These results show for inlet temperatures/equivalence ratios of 550 K/0.3, 600 K/0.2, and 600 K/0.3, the substrate temperature measured 3 mm, 38 mm and 97 mm from the leading edge versus time for different velocities. Note that for the lower velocity results, steady state conditions were not reached in all cases before the measurements were stopped. This fact was accounted for in making the following observations and comments.

a) 600 K/0.1/3 ms^{-1}

b) 600 K/0.2/3 ms^{-1}

c) 600 K/0.3/3 ms^{-1}

d) 600 K/0.1/2 ms^{-1}

e) 600 K/0.2/2 ms^{-1}

f) 600 K/0.3/2 ms^{-1}

g) 600 K/0.1/1 ms^{-1}

h) 600 K/0.2/1 ms^{-1}

i) 600 K/0.3/1 ms^{-1}

Substrate Axial Temperature Profiles at the Indicated
Times and at the Indicated Inlet temperature/Equivalence
Ratio/Velocity
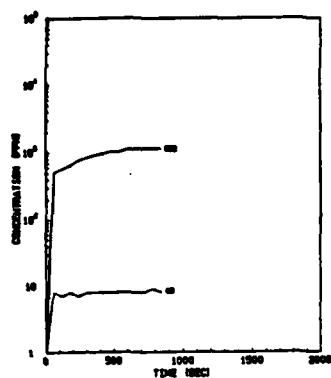
Figure 4

a) 600 K/0.1/3 ms^{-1} b) 600 K/0.2/3 ms^{-1} c) 600 K/0.3/3 ms^{-1}
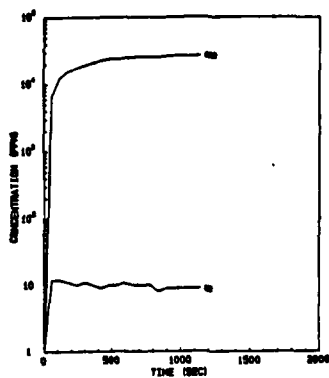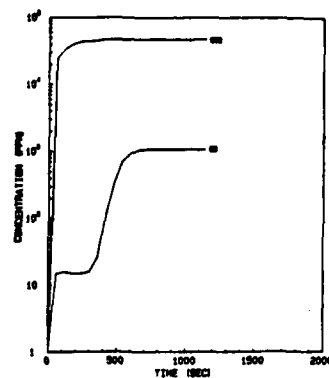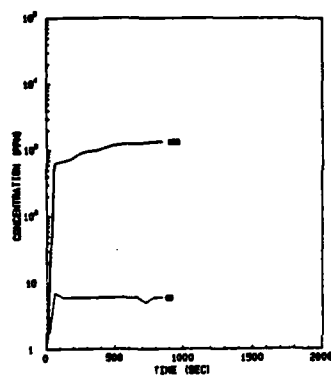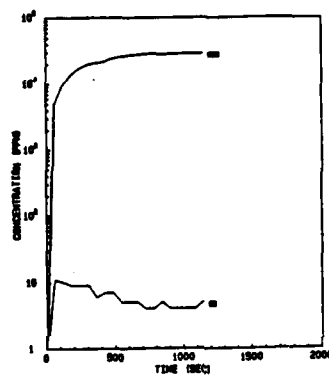
d) 600 K/0.1/2 ms^{-1} e) 600 K/0.2/2 ms^{-1} f) 600 K/0.3/2 ms^{-1}
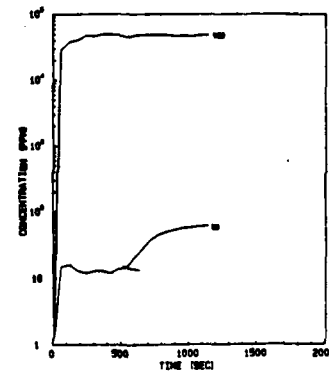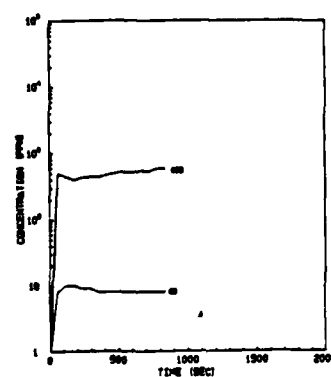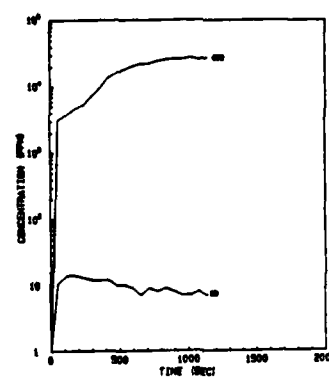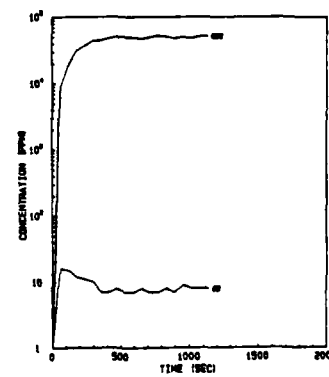
g) 600 K/0.1/1 ms^{-1} h) 600 K/0.2/1 ms^{-1} i) 600 K/0.3/1 ms^{-1}

Exhaust Gas CO and CO_2 Concentration Versus Time
at the Indicated Inlet Temperature/Equivalence
Ratio/Velocity

Figure 5
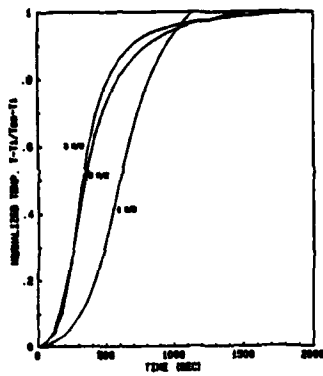
a) 97 mm/550 K/0.3   b) 97 mm/600 K/0.2   c) 97 mm/600 K/0.3

d) 38 mm/550 K/0.3   e) 38 mm/600 K/0.2   f) 38 mm/600 K/0.3

g) 3 mm/550 K/0.3   h) 3 mm/600 K/0.2   i) 3 mm/600 K/0.3

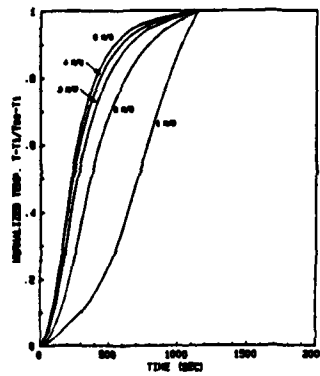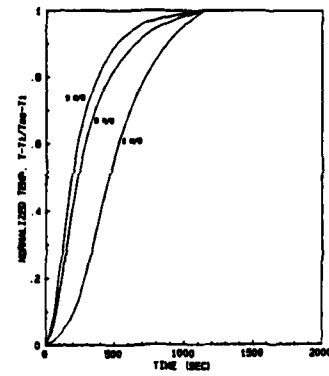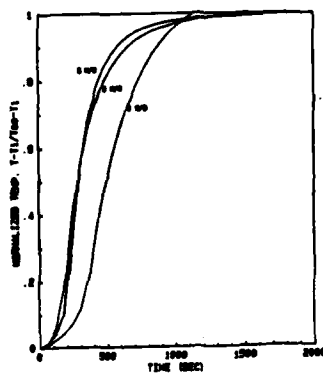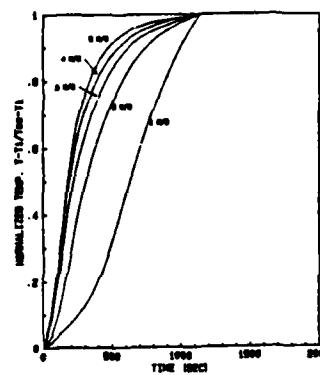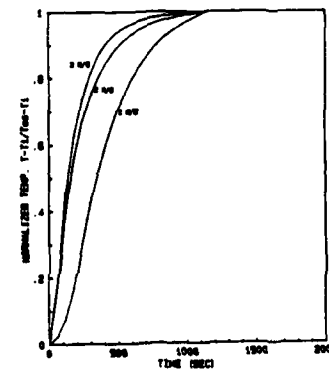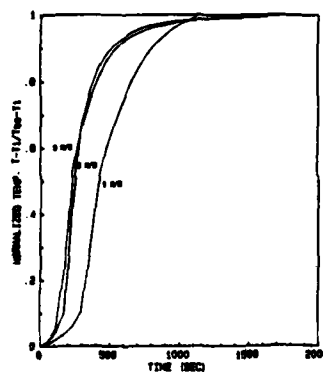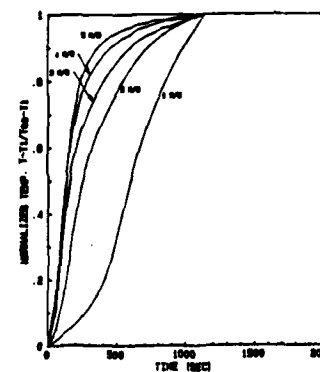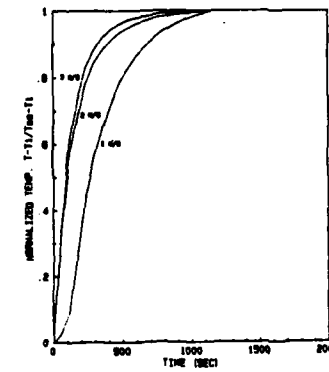Normalized Substrate Temperature Transients at the
Indicated Distance from the Leading Edge/Inlet
Temperature/Equivalence Ratio

Figure 6

The results in Figure 6 are what is in effect the local rate at which

the catalyst heats up. This heating rate is determined by the net effect

of the rate of heat release due to catalytic surface reactions minus the

rate of heat loss due to convective heat transfer to the gas, axial and

radial conduction in the catalyst substrate, and radiative heat transfer

within the catalyst channels and to the downstream and upstream test

section walls. The initial catalyst heating rate is due primarily to the

rate of fuel oxidation on the catalyst surface since the temperature

differences required for convection, conduction and radiation heat losses

are initially zero. The rate of fuel consumption is the net effect of the

rate at which fuel diffuses to the surface and the surface reaction rate.

If the mass transport rate is significantly less than the surface reaction

rate then the fuel conversion rate is said to be mass transfer limited. If

the surface reaction rate is significantly less, then the fuel conversion

rate is surface reaction rate limited.

With the above discussion in mind, the results shown in Figure 6 can

be analyzed. Consider first the measurements made near the leading edge of

the catalyst plate (6g, h and i). For all three cases when the velocity is

increased from 1 to 2 meters/second there is a pronounced increase in the

initial heating rate. This indicates that during the initial part of the

ignition process the local rate of fuel consumption is influenced by the

rate at which fuel diffuses to the surface. However, when the velocity is

increased above 2 meters/second, there is a much smaller change in the

initial heating rate, indicating that above 2 meters/second mass transport

has considerably less affect and suggesting that the initial ignition

process is surface reaction rate controlled. The effect of the surface

reaction rate can be seen by comparing Figures 6g and 6i where the inlet

temperature is the only parameter which changes. This comparison shows that for all three velocities there is an increase in the initial heating rate when the inlet temperature is increased.

In summary it appears that for the particular conditions of these experiments that below a certain velocity (approximately 2 m/s) the initial ignition rate near the leading edge of the catalyst is affected by both the mass transfer and the surface reaction rates, but as the velocity is increased (above approximately 2 m/s) the initial ignition rate is primarily surface reaction rate controlled. The surface reaction rate dependence of the initial ignition rate is to be expected due to the relatively low surface temperature. The fact that the initial ignition rate is not surface reaction rate limited at low velocities however is somewhat unexpected and suggests the possibility that the initial surface reaction rate may be greater than the steady state surface reaction rate (at the same conditions). Such behavior has been observed in transient surface kinetics experiments [7] and is due to the initial relatively large number of active sites on the catalyst's surface. This observation if correct could be very significant in that it shows that steady state surface reaction rates can not be used to predict catalytic ignition. It would also suggest that there may be advantages to cycling the fuel on and off and thereby achieving higher surface reaction rates.

The substrate temperature transients measured near the center of the catalyst plate (Figures 6d, e and f) and near the backend of the catalyst plate (Figures 6a, b and c) show very nearly the same behavior in terms of the effect of velocity and temperature on the initial ignition rate. Interpretation of any of the results shown in Figure 6 beyond the initial period however is very difficult due to the interrelated effects of the

surface reaction rate, mass and energy transport, conduction within the substrate and radiation heat transfer.

Oscillating Experiments: In the unsteady or oscillating catalytic combustion experiments the inlet temperature and velocity were fixed and the fuel was turned on and modulated in a simple on-off fashion. As in the ignition experiments, the substrate axial temperature profile and the exhaust gas CO and CO_2 concentrations were measured at 15 second intervals. Two oscillating cases and an equivalent nonoscillating case were investigated. The inlet temperature and velocity were the same for all three cases, i.e., 700 K and 3 meters/second. The time average equivalence ratio was also the same for all three cases. In the nonoscillating case the equivalence ratio was 0.25. In the oscillating cases, where the fuel was cycled on and off for 180 and 60 seconds respectively in one case and for 90 and 30 seconds respectively in the other case, the equivalence ratio was 0.33 when the fuel solenoid valve was open and zero when it was closed. In all three experiments the measurements began when the fuel was first turned on, where in the nonoscillating experiment the fuel was turned on and remained on, while in the oscillating experiments the fuel was cycled on and off as indicated above. Therefore, in all three cases the measurements were made through the ignition process until steady (or steady oscillating) conditions were reached.

The results from these experiments in terms of the substrate temperature measured 38 mm from the leading edge and the exhaust gas CO and CO_2 concentrations versus time are shown in Figures 7a-f.

The nonoscillating results shown in Figures 7a and d are consistent with the results of the ignition experiments (Figures 4-6). The substrate temperature transient (Figure 7a) does not exhibit the "S" shape observed
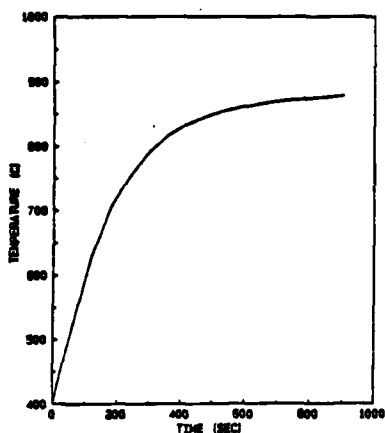
a)   Nonoscillating
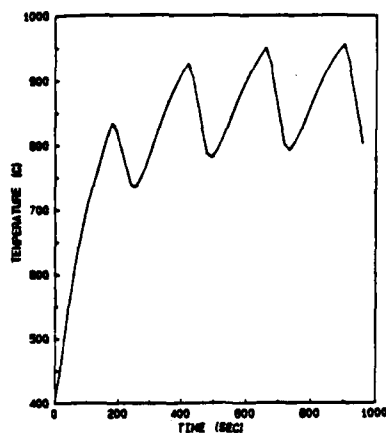
b)   Oscillating: 180/90 sec
     on/off cycle
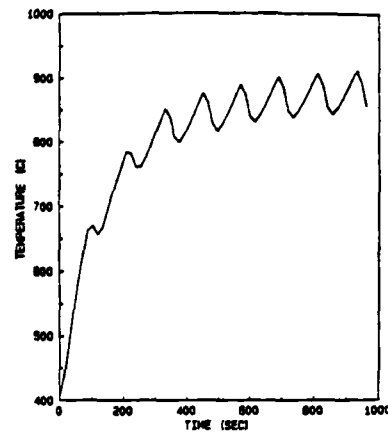
c)   Oscillating: 90/30 sec
     on/off cycle
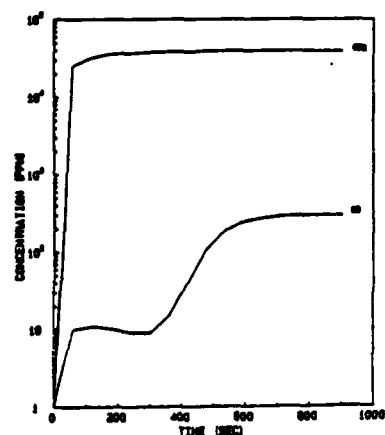
d)   Nonoscillating
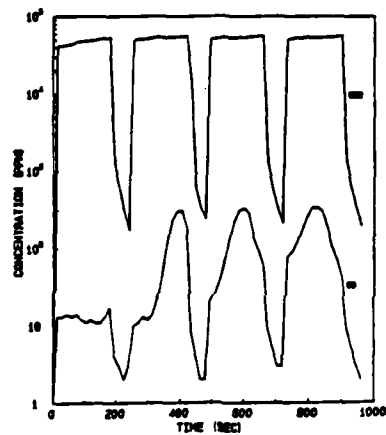
e)   Oscillating: 180/90 sec
     on/off cycle
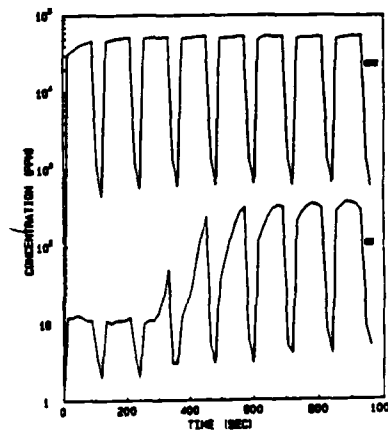
f)   Oscillating: 90/30 sec
     on/off cycle

Comparison Between Oscillating and Equivalent
Nonoscillating Experiments

Figures 7a-c: Substrate Temperature Measured
                38 mm From Leading Edge Versus Time

Figures 7d-f: Exhaust Gas CO and CO_2 Emissions
                Versus Time

Figure 7

when the initial ignition rate is mass transport controlled, therefore the initial ignition rate for this case is surface reaction rate limited. The CO_2 emissions are observed to increase very rapidly, to within 90% of their steady state value in 100 seconds, by which time the substrate temperature has only reached 850 K, compared to a steady state substrate temperature of 1150 K. The CO emissions begin to appeal after approximately 400 seconds, reaching 90% of their steady state value approximately 600 seconds after the fuel was first turned on.

For both oscillating runs the substrate temperature (Figures 7b and c) is observed to initially increase at a greater rate than the nonoscillating case due to the higher equivalence ratio (when the fuel solenoid value is open) and then to oscillate at the same frequency as the fuel supply modulation about a mean temperature which is very nearly equal to that observed in the nonoscillating case. The amplitude of the substrate temperature oscillation is shown to decrease with increasing oscillation frequency and one would expect that at some higher frequency the substrate temperature oscillation would completely disappear.

For both oscillating runs the CO_2 emissions nearly reach steady state the first time the fuel is turned on. The CO_2 emissions follow the fuel supply square wave cycle very closely, reaching steady state conditions shortly after the fuel is turned on. Therefore, there is no appreciable difference in the amplitude of the CO_2 emissions modulation as the oscillation frequency is increased. The oscillation period would have to be reduced to below at least 10 seconds to have an effect on the amplitude of the CO_2 emissions modulation. This however was beyond the response time capability of both the fuel delivery and the gas sample/analysis system. The oscillating substrate temperature and CO_2 emission results also clearly

demonstrate the previously observed fact that complete fuel conversion can be achieved at substrate temperatures substantially below the steady state peak temperatures. For example, consider the second fuel cycle. Immediately after the fuel is turned on, the CO_2 emissions reach steady state whereas the substrate temperature is still at 1025 K.

For both oscillating runs the fuel-on time is less than the characteristic time for gas phase reactions to begin during the first fuel cycle as would be indicated by the appearance of CO in the exhaust. The subsequent fuel cycles however start at higher substrate temperatures which reduces the time required for the onset of gas phase reactions. In the second 180/60 cycle (Figure 7e) there is a delay before CO is observed while in the third cycle CO is observed almost immediately after the fuel is turned on. In fact, in the third cycle the CO emissions are observed to peak and then decrease. This has been observed previously [8] in catalytic ignition experiments identical to those reported here but with an inlet temperature of 700 K and an equivalence ratio of 0.3 and is due to gas phase CO oxidation. In the 90/30 oscillating case (Figure 7f), CO is not observed until the third fuel cycle and only in the final cycle is there indication of a peak in the CO emissions. This illustrates the fact that by appropriately selecting the fuel cycling frequency, one can selectively exclude the gas phase oxidation of CO.

Premixed Turbulent Combustion

Although the study of the effect of turbulence on premixed turbulent flame structure will not begin until the second year of this grant, considerable efforts have been made during the first year in preparation for this work.
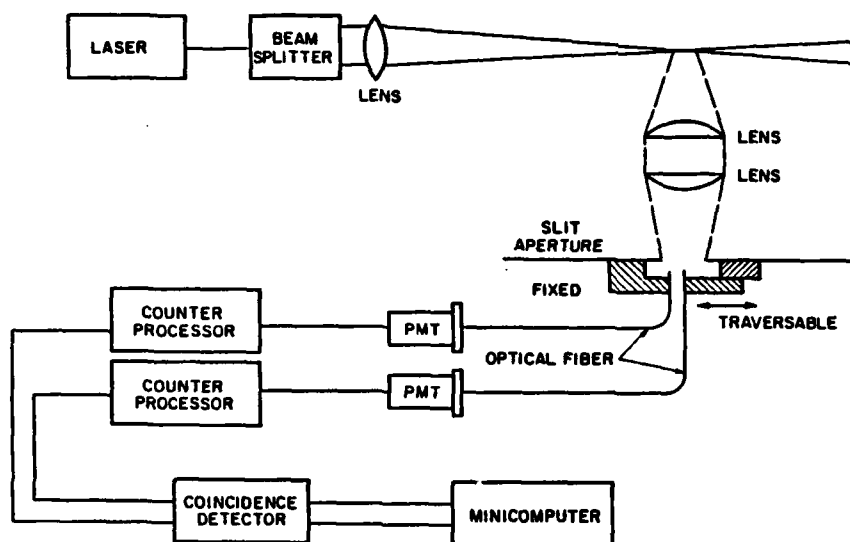
As mentioned previously an atmospheric pressure flow reactor has been constructed for the first phase of this work. A diverging test section with optical access has been built specifically for stabilization of a premixed turbulent flame. The basic concept of this design being that turbulence is generated at the inlet of the test section and that a flame which is ignited at the outlet of the test section will propagate upstream until the turbulent flame speed matches the gas velocity. The gas velocity will be increasing as the square of the axial distance, but it is important to realize that the turbulence will also be increasing as the flame propagates upstream. Very close to the turbulence generation device the turbulence will be largest and will be decaying the most rapidly. The turbulent flame speed is expected to scale nearly linearly with turbulence intensity, therefore close to the turbulence generation device the flame may continue to propagate despite the increasing gas velocity. However at some distance downstream of the turbulence generation device (approximately 50 to 100 integral length scales for grid generated turbulence) the rate of turbulence decay will be such that the flame can be stabilized in the diverging test section. The diverging test section has been used to successfully stabilize flames, but to date only at very low levels of turbulence where the flame structure appears to be strongly influenced by hydrodynamic instabilities. Further testing of this device awaits detailed characterization of the turbulence using the LDV system described below.

The LDV system for the detailed characterization of the turbulence ahead of and behind the flame has been acquired, set up and made operational this past year. This includes a specially constructed collection optics system for the two-point spatial correlation measurements from which the turbulence length scales can be directly determined. A

schematic drawing of this two-point LDV technique is shown in Figure 8. The LDV system has also been interfaced to an IBM PC/XT and the required data acquisition software written. In addition to measuring the turbulence intensity and length scale, measurements will be made of the spectral energy content in order to distinguish between the effects of small and large scale turbulent fluctuations (with respect to the characteristic scales of the flame itself). This requires that the time between velocity measurements be measured. The timing module required for this measurement is currently being designed. The ability to measure the time between measurements will be very useful from another point of view in that it will allow the effects of velocity bias to be assessed and possibly eliminated by using equal time sampling.

The 2-D flame structure measurement is illustrated schematically in Figure 9. In this experiment the premixed fuel/air is seeded with submicron titanium dioxide particles. Light from a pulsed Nd:YAG laser is focused into a laser sheet which is passed through the TiO_2 seeded turbulent flame. Light scattered from the laser sheet by the seed particles is imaged onto a 2-D solid state array camera which records a 2-D profile of the seed particle density through the turbulent flame. The resultant image clearly defines the turbulent flame structure. The solid state array camera and IBM PC based frame grabber data acquisition system has been acquired, set-up and made operational. The seeding system for introducing titanium tetracloride vapor which reacts with water in the air to form the required submicron titantium dioxide seed particles has also been constructed and tested. Currently efforts are being devoted to the development of the image processing and enhancement software required to optimize the definition of the flame boundary.

LASER → BEAM SPLITTER → LENS

LENS
LENS

SLIT APERTURE
FIXED
TRAVERSABLE

COUNTER PROCESSOR → PMT
COUNTER PROCESSOR → PMT

OPTICAL FIBER

COINCIDENCE DETECTOR → MINICOMPUTER

LDV SYSTEM FOR TURBULENT LENGTH SCALE MEASUREMENT

Figure 8

2-D FLOW VISUALIZATION OF PREMIXED TURBULENT FLAME STRUCTURE

FORMATTER → FRAME GRABBER → PSEUDO COLOR / VIDEO OUTPUT
RETICON CAMERA
IBM PC/XT
COLOR VIDEO MONITOR

Nd:YAG
LENS

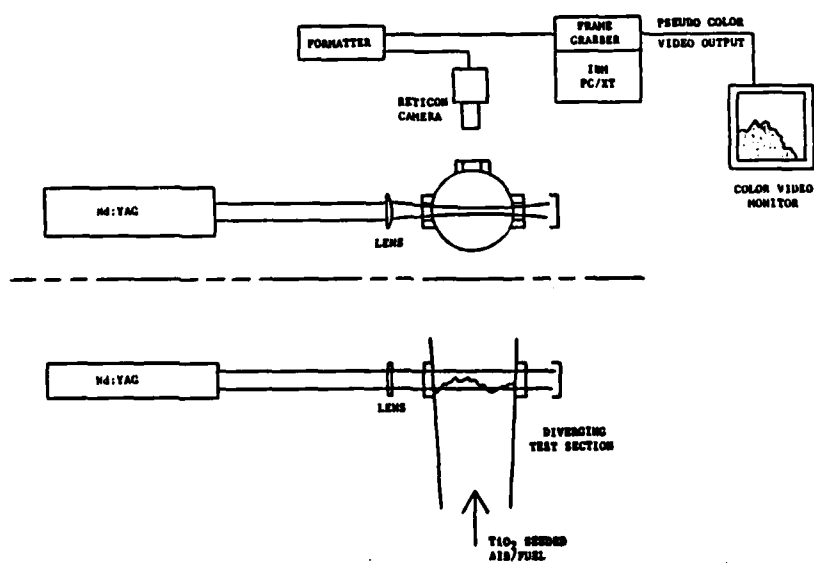Nd:YAG
LENS
DIVERGING TEST SECTION
TiO$_2$ SEEDED AIR/FUEL

Figure 9

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PERSONNEL

D. A. Santavicca, Principal Investigator

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G. North, graduate student

A. Sparago, graduate student

S. Murphy, undergraduate student

INTERACTIONS

During the past year the following researchers visited the Turbulent Combustion Laboratory:

R. Altenkirch, Univ. of Kentucky
A. Ghoniem, MIT

F. Bracco, Princeton Univ.
C. K. Law, U.C.-Davis

W. Cheng, MIT
S. Pope, Cornell

F. Dryer, Princeton Univ.
B. Sanders, Sandia

M. Dyer, Sandia
R. Santoro, NBS

A. Eckbreth, UTRC

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